

Ontario Hydro



RESEARCH DIVISION

91602
new 82-10

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if
Reproduced in Whole or in Part.



**ontario hydro
research division**

NONDESTRUCTIVE AND FRACTURE EVALUATION
SECTION
1983 REVIEW AND 1984 WORK PROGRAM

Report No 84-16-K

J.A. Baron
Supervising Engineer

ABSTRACT

The projects and achievements of the Nondestructive and Fracture Evaluation Section in 1983 are reviewed. Proposed projects and objectives for 1984 are described in outline.

job	file	date	report no.
740683-801-081	826.0	February 8, 1984	84-16-K

TABLE OF CONTENTS

	<u>Page</u>
I INTRODUCTION	1
II 1983 WORK PROGRAM REVIEW	4
1.0 FRACTURE MECHANICS RESEARCH AND APPLICATION	4
1.1 Plant Materials - Test Program	4
1.2 Plant Materials - Development of Test Methods and Instrumentation	9
1.3 Structural Integrity Evaluation of Plant Components	12
1.4 Structural Integrity Evaluation - Method Development	14
1.5 ASTM, CEA and Other Miscellaneous Activities	17
2.0 INSPECTION SYSTEMS DEVELOPMENT AND APPLICATIONS	19
2.1 CIGAR (Channel Inspection and Gauging Apparatus for Reactors)	19
2.2 Pickering NGSA - CIGAR-ette	20
2.3 Automated Scanning Systems for Ultrasonic Inspection	23
3.0 NDE TECHNIQUES R&D AND APPLICATIONS	25
3.1 Acoustic Emission	25
3.2 Ultrasonic Testing	28
3.3 Eddy Current Testing	30
3.4 Miscellaneous	31
4.0 GAUGING TECHNIQUES AND INSTRUMENTATION	32
III 1984 WORK PROGRAM OUTLINE	34
1.0 FRACTURE MECHANICS RESEARCH	34
2.0 NONDESTRUCTIVE INSPECTION RESEARCH AND DEVELOPMENT	36
IV SUMMARY	39
ACKNOWLEDGEMENT	42
1983 PUBLICATIONS AND CONFERENCE PRESENTATIONS	43
DISTRIBUTION	

CROSS INDEX BY CLIENT OR INTEREST GROUP

BRUCE NGS

	<u>Page</u>
Bruce HWP A Absorber Tower	12
Bruce A, Unit 1, Pump Discharge	12
Bruce A Unit 1 Pressure Tube L08	12
Fatigue Crack Growth Rates for Zr-2.5wt% Nb and Zircaloy-2 Pressure Tube Material	5
Fatigue Life Estimation of Bruce NGS "A" Steam Generator Tube	13
Bruce A Unit 1 - Ultrasonic Inspection of Pressure Tube L-08	25
BHWP - Acoustic Emission of an Absorber Tower	27
Bruce A Pressure Tube Leak Detection	27
BHWP - Inspection of E3 Hot Tower	29
Bruce B - Scanning Tool for Elongation Measurement (STEM)	32

CENTRAL NUCLEAR SERVICES

Reactivation of Orenda Burst Tests Rig and Initial Testing of Two Zr-2.5wt% Nb Pressure Tubes	6
Curved Double Torsion Fracture Toughness Tests Using Pressure Tube Segments	7
Fracture Toughness of A516 Gr 70 Pressure Vessel Material	8
Four Point Loading Double Torsion Jig and Furnace Assembly	10
Elastic-Plastic Fracture Mechanics - Numerical Method	16
Eddy Current Garter Spring Location Method	22
Eddy Current Gap Measurement	22
Ultrasonic Flaw Detection	21
CIGAR-ette	20-21
Quantization of Errors in Eddy Current Measurements	30
Pressure Tubes	12

CENTRAL SERVICES DIVISION

TWE -Hydraulic Cylinder from a Manlift Device	27
Hydraulic Cylinders for Manlift Devices	30

CENTRAL THERMAL SERVICES

Cost-Benefit Analysis on Thermal Plant Turbine Bolting	31
---	----

DESIGN AND DEVELOPMENT DIVISION

CIGAR (Channel Inspection and Gauging Apparatus for Reactors)	19-20
--	-------

	<u>Page</u>
<u>DOUGLAS POINT NGS</u>	
Direct Measurement Tools for Theodolite Measure- ment of Fuel Channel Elongation	33
Douglas Point NGS Fuel Channel Inspection	30
<u>DARLINGTON GS</u>	
Low Cycle Fatigue Properties of End Rings	9
<u>LAKEVIEW TGS</u>	
J _{IC} Testing - Thermal Plant Headers	11
Tandem Probe Inspection of Economizer Inlet Header	29
<u>NANTICOKE TGS</u>	
Fatigue Life Assessment of Governor Valve Spindle, Nanticoke TGS	14
<u>PICKERING NGS</u>	
Fracture Toughness of Zircaloy-2 Pressure Tubes with Radial Hydrides in Support of REFAB	5
Zircaloy-2 Pressure Tube Burst Tests in Support of REFAB	6
Zircaloy-2 Pressure Tube Delayed Hydride Cracking Tests in Support of REFAB	7
Application of DC Potential Drop Method to Zircaloy-2 with Radial Hydrides	11
Pickering A, Unit 3 Boiler Manway	12
Elastic-Plastic Analysis of Pressure Tubes with Blisters	13
Critical Crack Length of Zircaloy-2 Pressure Tubes with Radial Hydrides in Support of REFAB	13
Garter Spring Movement	25
AE Studies on the High Pressure System	26
Manway Hinge Removal Program	26
Pickering A - Inspection of Notches in ZrII Test Tubes	28
Pickering A - B-Scan of Boiler Manway	28
Pickering A - Mechanical Ultrasonic Scanner for Manway Inspection	29
Pickering NGSA - Miscellaneous CCTV Inspections	31
Pickering NGSA - Endshield Absolute Separation Measurement Device	32
Pickering A - Manual Feeder Clearance Tools	32
Pickering A - Laser Device for Pressure Tube (P/T) and Calandria tube (C/T) Sag Measurement	32
Pickering NGSA - Feeder Pipe Oxide Sampling Device	33

	<u>Page</u>
 <u>RESEARCH DIVISION</u>	
J Integral Tests Using Apple IIE Microcomputer	10
Stress Corrosion Experiments at NPD Rolphton	9
Computer Programs for Fracture Mechanics Testing	10
Computational Fracture Mechanics	14
Elastic-Plastic Fracture Mechanics - A Review	15
Finite Element Analysis on Surface Crack Problem	17
Participation in the ASTM Round Robin on Crack Arrest Toughness Testing	17
Automated Scanning Systems for Ultrasonic Inspection Preparations for PISC II International Round Robin	23
Robotic System Development	24
Robot Interface	24
C-Scan Software	24
Plotter Interface Software	24
Laboratory Automated Scanning Systems	24
Fast B-scan software	25
Inspection of Autoclaves	29
Remote Inspection of Used Fuel Containers	30
Research - Eddy Current Measurement of Pressure Tube Crevice Corrosion	31
Inspection and Consultations in Support of Research Division	31
CEA - EMATS	30

CROSS-REFERENCE BY WORK PROGRAM

	<u>Page</u>
<u>00 - GENERAL RESEARCH PROGRAMS - GENERAL</u>	
Inspection and Consultations in Support of Research Division	31
<u>41 - DISTRIBUTION SYSTEMS - OVERHEAD</u>	
TWE - Hydraulic Cylinder from a Manlift Device	27
Hydraulic Cylinders for Manlift Devices	30
<u>21 - ELECTRIC POWER SYSTEMS - ROTATING ELECTRICAL MACHINES</u>	
Low Cycle Fatigue Properties of End Ring	9
<u>50 - NUCLEAR GENERATION - GENERAL</u>	
Bruce HWP A Absorber Tower	12
BHWP - Acoustic Emission of an Absorber Tower	27
BHWP - Inspection of E3 Hot Tower	29
Elastic-Plastic Fracture Mechanics - Numerical Method	16
J-Integral Tests Using Apple IIE Microcomputer	10
Computer Programs for Fracture Mechanics Testing	10
Computational Fracture Mechanics	14
Elastic-Plastic Fracture Mechanics - A Review	15
Finite Element Analysis on Surface Crack Problem	17
Participation in the ASTM Round Robin on Crack Arrest Toughness Testing	17
<u>51 - NUCLEAR GENERATION - FUELS AND REACTORS</u>	
Bruce A Unit 1 Pressure Tube L08	12
Fatigue Crack Growth Rates for Zr-2.5wt% Nb and Zircaloy-2 Pressure Tube Material	5
Bruce A Unit 1 - Ultrasonic Inspection of Pressure Tube L-08	25
Bruce A Pressure Tube Leak Detection	27
Bruce B - Scanning Tool for Elongation Measurement (STEM)	32
Reactivation of Orenda Burst Tests Rig and Initial Testing of Two Zr-2.5wt% Nb Pressure Tubes	6
Curved Double Torsion Fracture Toughness Tests Using Pressure Tube Segments	7
Four Point Loading Double Torsion Jig and Furnace Assembly	10
Pressure Tube to Calandria Tube Gap Measurement	22
Garter Spring Detection	22
Ultrasonic Flaw Detection	21
CIGAR-ette	20-21
Pressure Tubes	12
CIGAR (Channel Inspection and Gauging Apparatus for Reactors)	19-20

	<u>Page</u>
Direct Measurement Tools for Theodolite	
Measurement of Fuel Channel Elongation	33
Fracture Toughness of Zircaloy-2 Pressure	
Tubes with Radial Hydrides in Support of REFAB	5
Zircaloy-2 Pressure Tube Burst Tests in Support	
of REFAB	6
Zircaloy-2 Pressure Tube Delayed Hydride Cracking	
Tests in Support of REFAB	7
Application of DC Potential Drop Method to Zircaloy-2	
with Radial Hydrides	11
Elastic-Plastic Analysis of Pressure Tubes	
with Blisters	13
Critical Crack Length of Zircaloy-2 Pressure	
Tubes with Radial Hydrides in Support of REFAB	13
Garter Spring Movement	25
Pickering A - Inspection of Notches in Zr II Test Tubes	28
Pickering NGSA - Miscellaneous CCTV Inspections	31
Pickering NGSA - Endshield Absolute Separation	
Measurement Device	32
Pickering A - Manual Feeder Clearance Tools	32
Pickering A - Laser Device for Pressure Tube (P/T)	
and Calandria Tube (C/T) Sag Measurement	32
Pickering NGSA - Feeder Pipe Oxide Sampling Device	33
Research - Eddy Current Measurement of Pressure	
Tube Crevice Corrosion	31
 <u>52 - NUCLEAR GENERATION - STEAM RAISING & HANDLING</u>	
Bruce A, Unit 1, Pump Discharge	12
Fatigue Life Estimation of Bruce NGS"A" Steam	
Generator Tube	13
Fracture Toughness of A516 Gr 70 Pressure Vessel	
Material	8
Quantization of Errors in Eddy Current Measurements	30
Pickering A, Unit 3 Boiler Manway	12
AE Studies on the High Pressure System	26
Manway Hinge Removal Program	26
Pickering A - B-Scan of Boiler Manway	28
Pickering A - Mechanical Ultrasonic Scanner	
for Manway Inspection	29
Stress Corrosion Experiments at NPD Rolphoton	9
Automated Scanning Systems for Ultrasonic Inspection	
Preparations for PISC II International Round Robin	23
Robotic System Development	24
Robot Interface	24
Plotter Interface Software	24
C-Scan Software	24
Laboratory Automated Scanning Systems	24
Fast B-Scan software	25
Inspection of Autoclaves	29

	<u>Page</u>
<u>61 - NUCLEAR WASTE - HIGH LEVEL WASTE & IRRADIATED FUEL</u>	
Remote Inspection of Used Fuel Containers	30
<u>72 - THERMAL GENERATION - STEAM RAISING & HANDLING</u>	
J _{IC} Testing - Thermal Plant Headers	11
Tandem Probe Inspection of Economizer Inlet Header	29
Fatigue Life Assessment of Governor Valve Spindle, Nanticoke TGS	14
Cost-Benefit Analysis on Thermal Plant Turbine Bolting	31
CEA - EMATS	30



**ontario hydro
research division**

To Mr. F.J. Kee
Director of Research

**NONDESTRUCTIVE AND FRACTURE EVALUATION SECTION
1983 REVIEW AND 1984 WORK PROGRAM**

I - INTRODUCTION

The Section incorporates specialization in two distinct areas - nondestructive evaluation and fracture mechanics. Whilst these disciplines are quite separate, they are closely bonded by the process of quantitatively assessing the structural integrity of materials and components under operational and laboratory conditions. This bond was well demonstrated in the work concerning thermal generating station headers where the NDE unit devised a method of measuring the extent of crack-ing whilst the Fracture Mechanics unit demonstrated that the component would leak rather than break. Thus the mission of the Nondestructive and Fracture Evaluation Section may be stated as:

"To research and improve the utility of present and potential Fracture Mechanics, Nondestructive Evaluation and Precise Spatial Measurement technologies as applied to the structural integrity assessment of structures, components and materials as used by the generation stations, transmission and distribution facilities within the specifications of the AECB and other controlling agencies."

In 1983, the Units' endeavours were mainly directed to support our Nuclear Program (91%). The year started with our involvement at Bruce NGS in searching for leaking pressure tubes and ended with an intensive effort in support of Pickering NGS, Units 1 and 2. In all 51% of the Section's work was funded by clients external to Research Division

A brief description of the interests of the Nondestructive Evaluation Unit and Fracture Mechanics Unit follows:

Fracture Mechanics Unit

Unit Head - Fracture Mechanics: Dr. B. Mukherjee

Engineers: Mr. M.L. Vanderglas
Dr. P.H. Davies
Dr. Y.J. Kim

Technologists: Mr. D.W. Carpenter
Mr. C.P. Stearns

Technician: Mr. D.M. McCluskey

The objectives of the Unit are:

- Assess the impact of flaws on off-design operation on the reliability and safety of major plant components.
- Propose and evaluate new methodology for flaw-structure interaction analysis that will quantify the real margins of safety of pressure bearing components.
- Improve quantitative understanding of the effects of plant chemistries, materials and fabrication processes and stress state on performance of major plant components.

The main research interests of the Unit are:

- Research into experimental and computational aspects of fracture mechanics.
- Determination of fatigue and fracture properties of generating plant and transmission system materials under operating environmental conditions.
- Investigation of techniques for service life prediction of components.
- Development of new material test methods and application of small specimen test results to predict load bearing capacity of full scale structures.
- Development of new fracture mechanics analysis procedures where conventional techniques are inappropriate.
- Development of rapid structural integrity evaluation methods to meet jurisdictional requirements.

Nondestructive Evaluation Unit

Unit Head - Nondestructive Evaluation: Dr. M.P. Dolbey

Engineers: Mr. W.K. Chan
Mr. E.G. de Buda
Dr. M.D.C. Moles
Mr. D.W. Donnelly
Mr. J.H. Sedo

Technologists: Mr. R.S. Algera
Mr. E. Bernacchia

Technicians: Mr. A.L. Allen
Mr. J.R. Boon
Mr. G.E. Truemner
Mr. B. Antonacci

The objectives and principal research interests of the Unit are:

- Design and development of remotely operated, electromechanical scanning system for nondestructive examination of nuclear station components to reduce man-rem expenditure and improve inspection reliability.
- Evaluation of new concepts and development of equipment to enable remote and precise spatial measurements in nuclear power stations.
- Research into limitations of and applicability of nondestructive testing techniques for defect detection and evaluation, particularly with regard to nuclear periodic inspection requirements.
- Development of new nondestructive techniques and procedures for particular applications at generating plants and transmission systems.
- Investigation of signal analysis methods for improved defect characterization.
- Assistance to the Operations Group with non-routine inspection problems, major system breakdowns, and service inspection requirements.

II - 1983 WORK PROGRAM REVIEW

1.0 FRACTURE MECHANICS RESEARCH AND APPLICATION

Overall goals of the Fracture Mechanics Unit are to determine material properties to provide quantitative material response input in structural integrity analyses and to provide technology and services to evaluate defect conditions in plant components. The review of the 1983 work program was organized to reflect these goals. Subsection 1.1 contains summaries of test programs conducted on actual plant materials used by Ontario Hydro and Subsection 1.2 describes work related to test method and instrumentation developments to support current and anticipated materials test program. Subsection 1.3 contains summaries of structural integrity analyses of pressure retaining or rotating components which contained some form of indications or imperfections. Some of these analyses were submitted to the regulatory authorities to justify continued operation of power plants. Subsection 1.4 describes projects which were conducted to develop computer and analytical methods to support structural integrity evaluation. Subsection 1.5 contains activities related to standard writing organizations such as ASTM and CSA.

1.1 Plant Materials - Test Program

During 1983 the Fracture Mechanics Unit conducted test programs using Zircaloy-2 and Zr-2.5% Nb pressure tube material, SA516 Gr 70 pressure vessel steel and associated temper bead repair welds and 18 Mn 4 Cr retaining ring steels. Approximately 30% of the Unit's resources were directed to the materials and metallurgical aspects of pressure tubes. This work was performed in collaboration with the Nuclear Metallurgy Unit. An extensive test program was conducted to determine the effects of temperature, hydrogen content and hydride continuity coefficient on the fracture toughness of Zircaloy-2. Pressure tube burst tests and delayed hydride cracking tests were performed using an experimental burst test rig at Hawker Siddeley, Orenda Division, Malton. A four point double torsion test jig and furnace have been constructed. The double torsion configuration is being used to test segments cut from Zircaloy-2 pressure tubes as part of a round robin test program with the Chalk River and Whiteshell Nuclear Laboratories. Fracture tests were carried out to generate toughness data for integrity assessments of repair welds in pressure vessel steels. Low cycle fatigue tests of 18 Mn 4 Cr generator end ring steels were conducted. Test results show that a dry hydrogen environment does not influence the low cycle fatigue properties of 18 Mn 4 Cr steel significantly.

Fracture Toughness of Zircaloy-2 Pressure Tubes With Radial Hydrides in Support of REFAB

The axial fracture toughness of Zircaloy-2 pressure tube material with radial hydrides was determined as a function of temperature. This work was performed in collaboration with the Nuclear Metallurgy Unit in support of REFAB for Pickering NGS A Units 1 and 2.

Tests were performed using compact tension specimens with 30 ppm (hydride continuity coefficient, $HCC < 0.3$), 40 ppm ($HCC = 0.3-0.45$), 60 ppm ($HCC \sim 0.5-0.6$) and 100 ppm hydrogen ($HCC = 0.5-0.6$ and $0.8-0.9$). At low and intermediate temperatures crack growth was governed predominantly by the presence of the radial hydrides and the fracture toughness decreased with increasing hydrogen concentration and increasing HCC. With increasing temperature the extent of through-thickness yield increased until at high temperatures crack growth was entirely governed by the flow properties of the matrix. Transition temperatures for full through-thickness yield or upper shelf behaviour of 175°C (30 ppm hydrogen), 200°C (40 ppm hydrogen), 235°C (60 ppm hydrogen), 260°C (100 ppm hydrogen, $HCC = 0.5-0.6$) and 280°C (100 ppm hydrogen, $HCC = 0.8-0.9$) were obtained ie the transition temperature increased with increasing hydrogen concentration and HCC.

For the 100 ppm hydrogen specimens and a few 60 ppm hydrogen specimens the fracture transition was very sharp, with a tendency for low fracture toughness (25-41 MPa $\sqrt{m}$) fast fractures at temperatures just below the transition temperature. In the upper shelf regime maximum load fracture toughness values > 150 MPa $\sqrt{m}$ were obtained independent of hydrogen concentration and HCC.

Fatigue Crack Growth Rates for Zr-2.5wt%Nb and Zircaloy-2 Pressure Tube Material

A report was issued summarizing measurements of fatigue crack growth of pressure tube material obtained in the Fracture Mechanics Unit during the past year. It was concluded that there is a lack of crack growth data for Zr-2.5wt%Nb and Zircaloy-2 pressure tube material relevant to reactor operation. The information was requested by CNS subsequent to the fracture evaluation of pressure tube defect L08, Bruce NGS "A", Unit 1.

Reactivation of Orenda Burst Test Rig and Initial Testing of Two Zr-2.5wt% Nb Pressure Tubes

A program of pressure tube material fracture testing has been undertaken at OHRD over the past several years to examine the issue of "leak-before-break" and to evaluate effects of hydride microstructure on the critical flaw size. The need for this work has been emphasized by the recent pressure tube leaks in Bruce Unit 2. An experimental burst test rig was reactivated during 1982 at Hawker Siddeley Canada Inc, Orenda Division, Malton.

Two sections of Zr-2.5wt% pressure tube were tested at 240°C. In the first test, as-received pressure tube material exhibited ductile, stable crack extension from a fatigue sharpened flaw prior to liner failure. In the second test, a tube which had been hydrided to 66 $\mu\text{g/g}$ with 40 $\mu\text{g/g}$ of radial hydride along the whole section at 240°C, failed by fast fracture with no ductile crack extension from a smaller, similar flaw. The hydride microstructure in the second test was completely radial and is representative only of the material in the highly stressed zones of over-extended rolled joints. Previous tests with high hydride concentrations have indicated similar results; this test indicates that intermediate hydride concentrations also significantly reduce fracture toughness at 240°C.

The results correlated well with the analysis of small compact tension tests of material with similar microstructure indicating that small specimens should prove very useful in conducting a parametric investigation of the fracture toughness behaviour of pressure tube material. However, additional information on stresses near rolled joints will be required to apply such results to cracks in the over-extended rolled joint zones of Pickering and Bruce pressure tubes.

Zircaloy-2 Pressure Tube Burst Tests in Support of REFAB

During 1983 three pressure tube burst tests were carried out at Orenda Ltd, Malton, using two Zircaloy-2 pressure tubes. Specimen 1 contained ~80 ppm hydrogen with hydrides reoriented under operating pressure to produce a mixed hydride morphology with a hydride continuity coefficient (HCC)~0.5. Specimen 2 contained ~80 ppm hydrogen with hydrides reoriented under twice operating pressure to produce mixed hydrides with an HCC~0.6-0.8.

Initially, each specimen contained two through-wall axial defects and was pressurized to failure at 240°C. Considerable through thickness yielding and bulging occurred around the defect areas for both specimens prior to liner failure at the longest defect. For specimen 1 the longest defect was 36.6 mm initially and grew to 39.7 mm prior to liner failure at a corrected hoop

stress of 259 MPa. For specimen 2 the longest defect was 22.8 mm initially and grew to 26.2 mm prior to liner failure at a corrected hoop stress of 333 MPa. The experimental hoop stress at liner failure was 4% less than the calculated plastic collapse stress for specimen 1 and at the calculated plastic collapse stress for specimen 2 after due allowance for slow crack growth.

Specimen 1 was subsequently patched and retested at room temperature with a single 28.0 mm long axial defect. Failure was by fast fracture with negligible slow crack growth at a corrected hoop stress of 130 MPa. This corresponded to a critical fracture toughness at room temperature, K_{IC} , of 37.9 MPa $\sqrt{m}$.

Zircaloy-2 Pressure Tube Delayed Hydride Cracking Tests in Support of REFAB

One leak-before-break test has been completed at Orenda Ltd, Malton. Four internal axial part-through notches were spark machined at each overextended rolled joint (4x5 mm long, 1.5 mm deep at endfitting E and 10, 20, 30 and 40 mm long, 1 mm deep at endfitting F) of a Zircaloy-2 pressure tube with radial hydrides (100 ppm hydrogen). Delayed hydride cracking occurred under an internal pressure of 9.7 MPa at 240°C after an initial thermal cycle to 300°C. After 88 hours leakage was detected close to the longest initial notch of nominal length, 40 mm and depth, 1 mm. Subsequent ultrasonic inspection by the NDE Unit at OHRD revealed significant through wall crack growth at the 20, 30 and 40 mm long notches although it was not possible to determine which defect had grown completely through the wall. After fitting a liner this specimen will be retested with the defects grown by delayed hydride cracking to failure.

A second Zircaloy-2 tube with radial hydrides (80 ppm hydrogen) containing four internal axial part-through notches at overextended rolled joints (4x5 mm long, 1.5 mm deep at endfitting C and 10, 20, 30 and 40 mm long, 0.5 mm deep at endfitting D) did not leak after 3-1/2 weeks on test. Subsequent ultrasonic inspection indicated only small crack extension at each defect. This tube has been put back on test.

Curved Double Torsion Fracture Toughness Tests Using Pressure Tube Segments

A four point double torsion test jig and furnace have been constructed for testing 51 mm long, 27 mm wide curved pressure tube segments at temperatures up to 300°C ie. reactor operating temperatures. A compliance calibration using a fatigue precracked specimen of Zircaloy-2 confirmed the linear

relationship between the elastic compliance and crack length over the range 20-35 mm. The resultant constant stress intensity factor/load relationship was within 1% of the strength-of-materials equation for a flat double torsion specimen.

The double torsion configuration is being used to test segments cut from pressure tubes as part of a "Round Robin in Fracture Testing of Pressure Tube Material". For Round Robin I the Zircaloy-2 pressure tube segment (629-159B) supplied by CRNL contained large circumferential hydrides with some radial hydrides close to the OD. The hydrogen concentration was 126 ppm. The lowest fracture toughness plane was the circumferential-axial plane, the curved cracks of the double torsion specimen growing away from the radial-axial plane towards the circumferential-axial plane at stress intensity levels $>15 \text{ MPa}\sqrt{\text{m}}$ and static loading rates ($\approx 1 \text{ MPa}\sqrt{\text{m}} \text{ sec}^{-1}$). A fracture surface similar to that of the fast fracture in the radial-axial plane of pressure tube 629-159B could only be obtained with the curved double torsion specimen by dynamic loading at $K \geq 10^2 \text{ MPa}\sqrt{\text{m}} \text{ sec}^{-1}$. Dynamic fracture toughness values at a load maximum, K_{cd} , varied from 67 to $81 \text{ MPa}\sqrt{\text{m}}$.

Fracture Toughness of A516 Gr 70 Pressure Vessel Material

In co-operation with the Welding Unit, fracture toughness tests were carried out in the heat affected zone (HAZ) of A516 Gr 70 steel. The objective of the tests was to generate HAZ toughness data for integrity assessments of weld repairs using non-post weld heat treated temper bead welds.

Three-point bending specimens were taken from two locations of HAZ, ie bottom HAZ and side HAZ. For the purpose of comparison, specimens were also taken from the base plate at two directions, ie parallel to the rolling direction and perpendicular to the rolling direction. The bottom HAZ specimens were tested in the temperature range of $-40^\circ \sim 280^\circ \text{C}$. Low temperature tests were carried out in a specially built environmental chamber. Other specimens were tested at room temperature. A proposed ASTM standard method entitled, "The Determination of J_{IC} , A Measure of Fracture Toughness" was used in the fracture toughness tests.

Test results show that HAZ toughness is virtually the same as the base plate toughness for the same specimen orientation. This implies that the toughness of HAZ is maintained after weld repairs. The bottom HAZ (weak direction) toughness data, at various temperature ranges, show large scatter.

Stress Corrosion Experiments at NPD Rolphton

A second batch of test specimens (3.75 cm thick compact tension) pre-stressed to $\sim 70 \text{ MPa}\sqrt{\text{m}}$ were installed into a secondary side steam environment in November, 1982. An interim report was recently issued, M83-203-K, to cover test data collected up to September 1983. It appears that little or no crack growth has occurred which will be confirmed when the specimens are removed for examination.

Low Cycle Fatigue Properties of End Ring

As a part of a continuing effort to generate material data for integrity evaluations of generator end rings in the hydrogen environment, low-cycle fatigue tests of 18 Mn-4Cr steel were performed. Fifteen cylindrical test specimens were prepared. The test sections were 10 mm long and 7.5 mm in diameter. Cyclic tests were performed under fully reversed strain-controlled conditions in air and hydrogen. An Apple IIe computer was interfaced with the signal outputs to follow load response, count cycles to failure and direct test data to a Hewlett-Packard digital plotter. Tests were conducted at $\pm 0.3\%$, $\pm 0.5\%$, $\pm 0.7\%$ and $\pm 1\%$ strain range. Test results show that a dry hydrogen environment does not influence the low cycle fatigue properties of 18 Mn-4Cr steel significantly. The cyclic stress-strain curves of 18 Mn-4Cr steel were also obtained by an incremental step testing. The stress-strain hysteresis loop shows that this material has a higher yield strength in compression than that in tension. The material data obtained in this testing program may be used to predict initiation and early crack growth in generator end rings.

1.2 Plant Materials - Development of Test Methods and Instrumentation

The work program in this subsection was developed to support current and anticipated materials test programs. Two Apple II+ computers were purchased. Each load frame in the Fracture Mechanics Laboratory has been equipped with an Apple computer. A number of specialized routines were written up to incorporate D/A and A/D interfaces in test control and data acquisition respectively. The computers were utilized to conduct single specimen J_{IC} tests using both three point bend and compact tension specimens, low cycle fatigue tests, fracture toughness tests of Zircaloy-2 and four point double torsion tests. A four point double torsion jig exhibiting high stiffness and thermal isolation through the use of ceramic loading columns has been constructed. A D.C. potential drop method was developed and used to monitor crack

extension during testing of compact tension specimens of Zircaloy-2. A capacitance type clip gauge was used to conduct single specimen J_{IC} tests at elevated temperature (200° and 300°C). Experimental data files were transferred from the Univac system to the Unit's Tektronix 4054 system to reduce storage costs.

Computer Programs For Fracture Mechanics Testing

Upon receipt of Tecmar D/A and A/D-timer interfaces, a number of specialized routines were written to incorporate them in MTS control and data acquisition, respectively.

Incremental tension and compression D/A routines suitable in compliance and J integral type piston control have been documented. Complementary linear regression and other data reduction routines have been written to suit the A/D test data input. Attention was also given to high speed data burst acquisition related to digital filtering. Similar routines have been used in acquiring a large block of data at high speed upon triggering.

J-Integral Tests Using Apple IIE Microcomputer

Several programs have been written and various electronic circuits fabricated to conduct J-integral tests for compact tension specimens and three point bend tests. Results obtained thus far have shown excellent agreement between optical crack extensions and those calculated through compliance calculations for both three point bend and compact tension specimens.

Four Point Loading Double Torsion Jig and Furnace Assembly

A four point double torsion jig exhibiting high stiffness and thermal isolation through the use of ceramic loading columns has been constructed. Loading is accomplished from the top by means of two stationary small diameter rollers mounted adjacent to each other in the top platen. In the bottom platen, loading and contact point translation are accommodated by larger diameter, wider spaced rotatable rollers. The rollers, which are hardened precision drill guides, rotate about and are supported by mating precision drill blank pins. The jig assembly provides double torsion loading for curved pressure tube specimens placed between the rollers such that rollers and specimen share the same horizontal axis direction at the outset of loading.

Heating of the specimen area is accomplished by means of aluminum collars containing cartridge heaters. The two collars, one around the top platen, and one around the bottom are externally insulated single piece construction to minimize temperature gradients and provide optimum heat transfer without jig distortion. Overall stiffness is achieved by compact dimensions and material properties.

Application of DC Potential Drop Method to Zircaloy-2 with Radial Hydrides

The dc potential drop method was used to monitor crack extension during testing of compact tension specimens of Zircaloy-2 with radial hydrides. However, the potential drop calibration obtained for fatigue precracked specimens was generally inadequate for calibrating each test. At low temperatures the potential drop calibration underestimated the nine point average crack extension by up to 60% due to short-circuiting across tight crack faces. At high temperatures the potential drop overestimated the nine point average crack extension by up to 100% due to through-thickness contraction at the specimen surfaces. It was shown that the calibration function also depended upon the instantaneous load and stroke. Under such circumstances it was necessary to calibrate each test specimen individually.

J_{IC} Testing - Thermal Plant Headers

A number of elevated temperature (200° and 300°) tests for J_{IC} were completed on the material (Al06B) from the Lakeview Economizer Header. Single specimens were periodically unloaded and a compliance technique was used to determine crack extension at each unloading. In this way, J_I-R curves were generated using a single specimen. In order to facilitate the use of compliance methods at such temperatures, a capacitance type clip gauge was used. Results of such testing show good agreement with multiple specimen, optical crack measurement methods.

Until recently, raw data from all J_{IC} testing has been processed on the Univac mainframe computer and reduced data has been stored in permanent files on the Univac system. However, such storage becomes increasingly costly as new files are added. To eliminate such costs, all files have been transferred directly from the Univac to a tape on the Tektronix 4054 system using a previously developed program.

1.3 Structural Integrity Evaluation of Plant Components

Structural integrity analyses were conducted for the following components:

1. Bruce A, Unit 1, Pressure tube L08.
2. Bruce A, Unit 1, pump discharge line.
3. Pickering A, Unit 3 boiler analysis.

A parametric study of crack opening deflection and stress intensity factor was performed for pressure tubes in general. A fatigue evaluation of Bruce A steam generator tubes was performed to determine the number of cycles required for a defect to penetrate through the tube wall. Critical crack lengths for Zircaloy-2 pressure tubes with radial hydrides were calculated for Pickering NGS A, Units 1 and 2 using fracture toughness measurements from small specimens.

Structural Integrity Evaluations

Fracture mechanics evaluations of defects in the following components were performed: (i) pressure tubes: parametric stress studies of crack opening deflections and stress intensity factors for axial cracks near the endfitting were performed to investigate the effects of endfitting constraint, crack size and position and residual stresses. (ii) Bruce A, Unit 1, pressure tube L08: a Section XI analysis was performed for an internal defect near the tube's center. (iii) Bruce A, Unit 1, pump discharge: a parametric study of the effects of vibration stress amplitude and frequency was performed. (iv) Pickering A, Unit 3 boiler manway; a section XI evaluation of a large number of indications in the manway/shell weld was initiated, to be completed early in 1984. Bruce HWPB absorber tower: an analysis of a small internal defect midway along the tower was performed.

Elastic-Plastic Analysis of Pressure Tubes with Blisters

An elastic-plastic analysis of pressure tubes containing blisters was initiated as a part of a task for determining the time between PT/CT contact and fast fracture. The objective of the project is; (a) to determine stress fields associated with blister formation singly and in array, and (b) to determine crack driving forces at crack tips associated with blisters. In order to account for the large amount of volume expansion of blisters, an elastic-plastic analysis is required. Although the nature of the problem represents a three-dimensional case, initially, a two-dimensional model on a flattened tube was used to save computing effort.

Preliminary results from a single blister analysis show that the plastic zone created by 14% volume expansion of a blister extends to the distance of a blister size. Although compressive stresses were created along the radial direction of the pressure tube, tensile stresses higher than the yield strength of the pressure tube were observed along the hoop direction.

Fatigue Life Estimation of Bruce NGS "A" Steam Generator Tube

A fatigue evaluation of Bruce NGS "A" steam generator tube was performed to determine the number of cycles required for a defect to penetrate through the tube wall. The analysis was based on a conservative two dimensional model of an edge crack, acted upon by the cyclic stress due to flow induced vibration. Due to the unavailability of a Bruce NGS "A" steam generator stress report, the Bruce NGS "B" steam generator stress report was used. Based on available information (stresses from the Bruce "B" stress report and fatigue properties found in literature), it was estimated that it takes approximately 6 months at 30 Hz for a defect to penetrate through the tube wall.

Critical Crack Length of Zircaloy-2 Pressure Tubes with Radial Hydrides in Support of REFAB

Critical crack lengths (CCL) for Zircaloy-2 pressure tubes with radial hydrides were calculated for Pickering NGS A Units 1 and 2 using fracture toughness measurements from small specimens. The CCL clearly reflected the variation in fracture toughness with temperature. For 30 ppm hydrogen ($HCC < 0.3$) room temperature CCL's of 33 to 36 mm (inlets) were predicted decreasing to 21 mm (inlets) for 100 ppm hydrogen ($HCC = 0.8-0.9$). For 60 ppm hydrogen ($HCC = 0.5-0.6$) and 100 ppm hydrogen ($HCC > 0.5$) large values of CCL above 100 mm were only ensured at temperatures at or above the transition temperature.

Fatigue Life Assessment of Governor Valve Spindle, Nanticoke TGS

The fatigue life of the threaded region of a governor valve spindle was assessed. If an assessment is based on room temperature material properties, the component is not likely to fail during service life. However, considering the high operating temperature (540°C), the threaded region is likely to fail by fatigue loadings. Due to the unavailability of fatigue data at operating temperature, recommendations for a limited testing program were made.

1.4 Structural Integrity Evaluation - Method Development

Development of computational linear elastic fracture mechanics techniques was directed at the following areas:

1. ASME Section XI evaluation of defects in power plant components.
2. Feasibility of conducting finite element (FE) analysis on a minicomputer.
3. Elastic analysis of three dimensional (3D) cracks. If successful, this technique may provide a cost-effective method for calculating the stress intensity for 3D cracks.

Recent developments on elastic-plastic fracture mechanics methodologies were reviewed and were presented at a departmental seminar. A general purpose computer program, ABAQUS, was used to calculate elastic plastic crack driving forces on a three point bend specimen and a circumferentially flawed pipe with axial and bending loads. The ABAQUS code was also utilized to analyse a plate with a part-through crack subjected to tension and bending loads.

Computational Fracture Mechanics

Development of a computational fracture mechanics technique was directed at the following areas:

1. ASME Section XI evaluations of defects in power plant components.
2. Feasibility of finite element (FE) analysis on a minicomputer.
3. Elastic analysis of three dimensional (3D) cracks.

A program to perform the SECT XI fatigue calculations was written for a Tektronix 4054 desktop computer. It was subsequently used for a number of structural integrity assessments. The flexibility and fast "turn-around" available when such analysis is performed on a desktop (versus main frame) computer was demonstrated, especially for an evaluation of a Bruce pressure tube defect which was completed in a day. A similar program was written to perform the fatigue calculation for multiple defects. In this case, the desktop computer's computational speed was too slow and the program was rewritten for a main frame instead.

The computer costs associated with FE stress analysis can be quite high. An attempt was made to eliminate this cost by implementing an existing program on a DEC 11/44 minicomputer. Unfortunately, it became clear that, because of the computer's relatively small memory, the program would have to be extensively modified and even then, the limit on problem size would be too small for practical applications.

The weight function technique for the calculation of stress intensity factors (K) was refined for two dimensional analysis of cracks. A parametric study of K for eccentric embedded cracks was performed since the defects found during inservice inspections are frequently of this type, and the literature has solutions only for membrane stresses: results allow calculation for any stress distribution.

Few techniques are available for the calculation of K for 3D cracks, none exist to obtain the weight functions. From the results of numerical experiments with 2D weight functions, a 3D approach was devised. It requires an exact solution for a crack in an infinite region, and finite element software which can be modified to implement the technique. A FE program, dedicated to 3D elastostatic analysis was prepared and some test cases were run. It was felt that, by optimizing the code for 3D analysis only, computer costs could be minimized. Especially in 3D generation of the data to represent the geometry and boundary conditions usually contributes most to the cost and time required for FE analysis. Consequently two interactive, graphics oriented programs were written, one to generate the geometric model, the other to produce boundary condition data (applied forces, deflections, etc). These programs were structured to permit the inevitable future modifications required to handle more complex geometries. The weight function technique requires an exact solution for K due to a point load placed anywhere in an infinite region. Such a solution was derived since apparently, none exists in the literature. Although it correctly reproduces a few known solutions for particular cases, a more detailed verification is still required.

Elastic-Plastic Fracture Mechanics - A Review

Recent developments on elastic-plastic fracture mechanics methodologies, ie EPRI engineering approach and CEBG FAD (Failure Assessment Diagram) approach, were reviewed. The essence of EPRI approach is to tabulate fully plastic J solutions for various geometries and loading conditions, and to define the method for estimating elastic plastic J values. Graphical methods, such as J- Δa curve and J-T (tearing modulus) curve, were developed for predicting crack initiation, stable crack growth and instability by combining the crack driving force estimates with a resistance curve determined from standard

specimen tests. The CEBG FAD approach is based on the idea that failure is bounded by LEFM at one extreme and plastic collapse at the other and that two mechanisms are connected by a transition curve so that the analyst can go directly from linear elastic failure behaviour to plastic collapse.

In general, CEBG FAD approach is convenient in a preliminary investigation of the safety margin of a flawed structure. In marginal situations where the assessment point lies in close vicinity of the failure line, a more detailed evaluation using J- Δa curve or J-T curve yields a more precise estimate of the margin. Also the CEBG failure assessment line ignores the effect of structure geometry, loading type and material deformation properties. These effects can be included on the assessment line by combining it with EPRI engineering solutions.

Elastic-Plastic Fracture Mechanics - Numerical Method

An important step in the evaluation of flaws using elastic-plastic fracture mechanics methodologies, is the determination of crack driving forces, ie J-integral and COD. Closed form J solutions are known for a relatively small number of simple geometries. For more complex structures, an analytical technique such as the finite element method is required. In order to develop capabilities for obtaining J values numerically, selected case studies were performed.

A two-dimensional elastic-plastic analysis of a three-point bend specimen, a specimen commonly used for the fracture toughness measurement of a material, was performed using the general purpose finite element program, ABAQUS. The specimen was modelled with eight-node quadrilateral isoparametric elements while crack tip singularity was modelled with collapsed quarter point elements. The Virtual Crack Extension (VCE) method which calculates the generalized forces by performing a small perturbation to the geometry of the body was used to compute J values. J values were computed at each load increment for four contours passing through the successive layer of elements surrounding the crack tip. In the elastic range, computed J values are in good agreement with theoretically obtained ones. The difference is within 2%. Also in the elastic-plastic range, computed J values show a good agreement with other numerical results such as those from an ASTM round robin test program. Numerically obtained load vs load point displacements also show good agreement with other results.

A three-dimensional elastic-plastic analysis of a pipe with a circumferential crack subjected to axial and bending loads was also performed. The pipe was modelled with 71 twenty-noded brick elements. Again, quarter-point elements are collapsed toward the crack front to give the singularity at the crack tip. J values are computed as a function of position along a crack front using a VCE technique. Preliminary results show that inner surface J values agree well with outer surface J values,

while J values degenerate quickly as the integration line moves away from the crack tip.

Finite Element Analysis of a Surface Crack Problem

A two-dimensional finite element analysis of a plate with a part-through crack subjected to edge tension and bending was conducted. The line spring elements in ABAQUS code was utilized for the analysis. The basic concept of these elements is that they introduce the local solution, dominated by the singularity at the crack tip into a shell model of the uncracked geometry. The relative displacements and rotations across the cracked section, calculated in the line spring elements, are then used to determine the magnitude of the local strain field and hence the J-integral and stress intensity factor values, as functions of position along the crack front. In comparison to a 3-D finite element analysis, the numerical results obtained show a good agreement over the middle portions of the flaw but the accuracy decreases at the ends of the flaw. In general, the line spring elements provide an inexpensive evaluation of the effect of surface flaws in shell structures with sufficient accuracy.

1.5 ASTM, CEA and Other Miscellaneous Activities

Committee Activities

A member of the Unit acted as a monitor for a CEA project on the Use of Side-Grooved Precracked Charpy V Notch Specimen Technique for Estimating Fracture Toughness, which was awarded to Hydro-Quebec. The Unit also participated on a committee which was organized by the newly formed NRC - Institute of Materials Research to determine the extent to which Canadian Industries are affected by ductile fracture.

Participation in the ASTM Round Robin on Crack Arrest Toughness Testing

In order to encourage the use of linear elastic fracture mechanics to generate information on crack arrest toughness, a cooperative test program was conducted under the auspices of the ASTM E-24 Committee on Fracture in 1977. A proposed ASTM Test Method for Crack Arrest Fracture Toughness of Ferritic Materials has been developed from the experience of the co-operative test program. It is anticipated that an ASTM round robin on crack arrest testing will get under way in early 1984. In this task, crack arrest fracture toughness will be determined in two steels (A533B Pressure Vessel steel, A588 bridge steel) following the procedures indicated in the proposed ASTM method. The Fracture Mechanics Unit will be participating in this round robin testing program. A test jig for conducting these tests has been fabricated.

Bid for External Projects

A proposal for the measurement of crack arrest toughness of plate steels used in offshore structures and arctic vessels has been submitted to the Supply and Services Canada. The Unit is committed to provide approximately 2-1/2 man years to this project over 1984 and 1985, if the proposal is accepted.

Help and Assistance to Other Units

Help and assistance were provided, on request, to other Units within the Research Division in the areas of computing, instrumentation and materials testing. Test specimens were precracked for the Corrosion and Thermal Plant Metallurgy Units of the Corrosion and Thermal Plant Section. Specimens were precracked and preloaded for the Steam Generator and Nuclear Waste Corrosion Unit of the above Section. Through wall axial fatigue cracks were produced on 150 mm diameter aluminum tubes for the Nondestructive Evaluation Unit. Some assistance with regard to the use of ABAQUS computer code and fatigue life evaluation methods was provided to the Applied Structural and Solid Mechanics Section.

2.0 INSPECTION SYSTEMS DEVELOPMENT AND APPLICATIONS

2.1 CIGAR (Channel Inspection and Gauging Apparatus for Reactors)

The inspection system known as CIGAR is being developed to inspect and gauge pressure tubes in the core of Ontario Hydro's CANDU Reactors. The system consists of an inspection head, carrying inspection and gauging transducers, that is driven down the full length of a defuelled, water filled fuel channel by a drive system mounted on the reactor fuelling machine bridge. Drive system operation inspection system data acquisition and processing are controlled from a location outside the reactor vault. CIGAR has been under development since 1975 and commissioning trials were scheduled for 1983. However, due to the pressure tube rupture at Pickering Unit 2, in mid 1983, effort and equipment required to complete CIGAR had to be diverted to the more immediate need. This brought work on CIGAR virtually to a stop during the last 2 months of 1983. Work should recommence in February 1984 with the delivery of replacement drive rods and inspection heads.

Early in 1983 the emphasis in CIGAR work was placed on the continuation of data acquisition and playback software development and on the preparation of the Pump Test complex to receive CIGAR drive when it was sent to Hydro from CGE in Peterborough. After the equipment arrived in August, the emphasis shifted to trouble shooting both hardware and software problems with the received drive and to the integration of the inspection systems. To simplify the description of 1983 work, each major CIGAR system or topic will be described separately.

Ultrasonic Flaw Detection

At this time, ultrasonic flaw detection is essentially complete. The data acquisition and playback software is very far advanced. Software for the general helical, detailed axial, and detailed circumferential scans is essentially complete. Other scan software will follow directly from that which is already complete.

Gauging

The gauging system hardware and software were essentially complete in 1982. Some additional software has recently been written to be used in trouble shooting the gauging system. Some work has also been done on locating and correcting a minor periodically appearing data transmission problem between the Local and Remote Gauging Modules.

Sag

Sag data acquisition software was also completed in 1982; however, a large portion of the playback software was completed this year. This software was written by the I&C section of Design and Development. An investigation is currently underway into possible electrical noise problems in the sag system. Also, work has been done to try to improve the water-tightness of the sag module as water leaking into the system has caused unstable results in the past.

Gap

The eccentricity method of measuring gap was re-evaluated and new experimental data was collected and analyzed. The results indicated that the accuracy of the method may have been overestimated in the original development work done. Currently, work is underway on developing a reliable point-by-point gap measurement system. This point-by-point method has been successfully demonstrated at Pickering, Units 1 and 2.

CIGAR Drive Software

Since the CIGAR rig arrived in August, a considerable amount of experimentation has been done with it and with the drive software written by CGE. A large number of problems and inadequacies have been identified in the software and these are being worked upon by engineers from I&C section of Design and Development.

CIGAR Hardware

Although some problems have been identified with the CIGAR hardware, and for the most part already corrected, the biggest issue in hardware is its lack of availability. Significant portions of the CIGAR hardware have been taken for use on the Pickering Unit 1 and 2 pressure tube inspections. This loss of equipment has greatly limited the amount of progress that can be made towards the completion of the total CIGAR inspection system.

2.2 Pickering NGS - CIGAR-ette

The rupture of a pressure tube in Pickering Unit 2 led to a need for large scale fuel channel inspection. The CIGAR system was considered but rejected for the following reasons:

1. There was uncertainty whether it could be completed in time.
2. If used in an incomplete state, it would become contaminated and further development would become very difficult.
3. Manufacture of additional drives would require more than a year so that inspection of more than one unit at a time would not be possible. Also any break down of the one unit would stop all inspection.

It was decided to develop a system using the existing CIGAR drive rods and in-channel components (closure/carrier and inspection head), the CIGAR inspection systems without sophisticated data gathering capabilities, and a pinch-roller drive developed by AECL. CNS administered the system. Research Division have contributed in the following areas:

Design Requirements

Assistance was provided to AECL during the initial stages of the CIGAR-ette drive design in establishing the design requirements and possible drive concepts.

Inspection System Hardware

Specifications were written for the required inspection systems instrumentation to be acquired by CNS. The manufacture of 9 additional inspection heads was arranged. They were assembled and tested at the laboratory before delivery to the station. Maintenance of the inspection heads that had been in service was also performed. All inspection system cabling between the inspection head and the instruments was supplied including reactor vault penetrations. Considerable effort was required to improve the rod-end connector cabling to overcome damage due to mechanical strain.

Inspection Systems

The inspection systems utilized on CIGAR-ette are Ultrasonic flaw detection using 2 opposed axial and 2 opposed circumferential 45° shearwave transducers, an eddy current method of locating the garter spring spacers and an eddy current method of measuring the gap between the pressure tube and the calandria tube. Research supplied inspection procedures, operator training and assistance with data reduction and interpretation.

Ultrasonic Flaw Detection

An inspection procedure was written in conjunction with J. Leslie, CNS, covering drive console operation and ultrasonic flaw detection and measurements. Several groups of operators have been familiarized with the operation of the Krautkramer KB6000 multichannel flaw detector at Research. At Pickering, assistance was given to the inspection crews, especially at the early stages, to help start the CIGAR-ette inspections. A modification was made to the CIGAR Zr II ultrasonic transducer modules to remove a standing wave, and line focussed probes are being investigated to determine whether the inspections can be speeded up.

The ultrasonic data were recorded on a 14 channel analog tape recorder. Part of the CIGAR system was modified to provide a computer assisted playback of these data in the form of isometric display of signal amplitude against axial and circumferential position.

Video recording of the A-scan data of the 4 transducer ultrasonic system is also provided.

Eddy Current Garter Spring Location Method

An eddy current probe was developed for the detection of fuel channel garter springs during dry channel inspections. The probe is a bridge type differential coil, about 100 mm in diameter, and is designed to induce eddy currents in the girdle wire of the garter spring. The probe was successfully tested in a mockup and then used to locate garter springs in tube J15 of Pickering Unit 2. Subsequent use by CNS in Bruce Unit 6 and Pickering Unit 8 showed that cable integrity, equipment grounding and delivery system alignment are critical for optimum signal to noise ratio. Satisfactory performance was obtained for vertically oriented garter springs but the signal to noise ratio was borderline for slanted garter springs in some tubes.

Another probe was designed to fit the CIGAR inspection head for use in fuel channels still flooded with coolant. This coil is based on the same principles described above but instead of a full 360° coil, it is a spring loaded 120° wedge. The signal to noise ratio obtained from vertically oriented garter springs was reduced from that seen with the 360° probe. However, the 120° probe can be rotated to an orientation which produces a signal to noise ratio for a slanted garter spring that is almost as good as that obtained from a vertical garter spring. As a consequence a number of scans at different rotational positions are required in order to ensure that all garter springs are located. This probe has been used with the CIGAR-ette inspection system during examination of channels in Pickering Units 1 and 2. In general, garter springs have been located with a high degree of confidence in most channels. In the cases where noise problems were encountered, they were shown to be primarily due to poor signal cable integrity.

Eddy Current Gap Measurement

An eddy current based measurement system capable of measuring point values of pressure tube to calandria tube gap has been developed and tested. The signal produced by the system is primarily sensitive to gap and pressure tube wall thickness variations. Therefore, in order to calculate gap values,

wall thickness data are required from an independent system. These data are supplied by an ultrasonic system previously developed for CIGAR and is currently limited to an accuracy of $\pm 1\%$.

A computer program has been written for an Apple computer which calculates the gap value from eddy current and wall thickness information. The program uses an accurate and fairly extensive data base of experimental eddy current signals measured from various gap and wall thickness combinations set up in the laboratory.

The eddy current probe was previously developed for the eccentricity measurement system of CIGAR and so both parts of the gap systems were readily available for the CIGAR-ette inspection of Pickering Units 1 and 2. Initial tests at Pickering were promising but with continuous use, some irrational results were obtained. The problem has recently been shown to be mainly a consequence of poor signal cable integrity. Equipment is now under development by the Non-destructive Evaluation Unit and the Electronic Design Section to simplify cable testing. In addition procedural changes have been made which allow for easier detection of a malfunctioning system.

Good results have now been obtained from a number of fuel channels at Pickering. The gap figures have been reported with an accuracy of $\pm (30\% + .1 \text{ mm})$. This error estimate is largely based on the accuracy of the wall thickness measurements.

2.3 Automated Scanning Systems for Ultrasonic Inspection

Preparations for PISC II International Round Robin

The direction of the Canadian participation in the PISC II RRT (Round Robin Test) was reviewed. It was felt that the full intent of the robotic inspection system development program would not likely be achieved to meet the PISC II inspection schedule in 1983. A decision has been made to withdraw Ontario Hydro's participation in the RRT and the establishment of other test programs will be considered. However, the decision has not jeopardized the development program of robotic ultrasonic inspection systems. The program has been redirected to inhouse development for UT techniques and procedure validation more suited to the materials and geometries of direct relevance to CANDU nuclear plants. A further review of the program requirements for the robotic UT inspection system is underway. A new set of goals will be established. This will include the adaptation of the equipment to remote inspection capability in field applications.

Robotic System Development

A prototype ultrasonic scanning system which uses a Unimate PUMA 560 industrial robot has been developed. This system can cope with a variety of curved shapes and shows considerable promise. So far it has been used to inspect some steel elbow cutouts from Bruce NGS and was used to assess the feasibility of inspecting the Bruce HWP towers.

Robot Interface

Interface software has been written to link the Unimate PUMA 560 industrial robot to the Apple II+ microcomputer, allowing two way communication. Commands, status, data, and coordinate locations can be transmitted. This allows much more flexibility with the robot motion control and simplifies the incorporation of instrumentation and other devices into the robotic system.

Laboratory Automated Scanning Systems

Improvements were made to a number of laboratory automated scanning systems besides the robot. The general purpose tank scanning facility (blue tank) was refitted with new ballscrews to eliminate backlash. A high speed motor for the longest axis has been fitted but not yet electrically integrated.

The laboratory CIGAR test rig was integrated with an Apple II+ allowing the existing B-scan and C-scan software to be used (see below).

A number of components of another small more versatile scanning system were acquired in 1983. They have been used in various combinations for special inspections and for testing concepts of applications.

C-Scan Software

The laboratory test tank C-scan software has been modified to give it additional capabilities. These include the ability to use it with the Bruce header inspection device and the laboratory CIGAR test rig. Also it can now be used with digital or analogue signals and can now code the scans according to distance as well as amplitude.

Plotter Interface Software

Graphical output from fast B-scans and other ultrasonic scans can now be easily plotted out in colour on the HP 7470A colour plotter. Speed is limited only by the speed of the plotter.

Fast B-Scan Software

High speed B-scans are now possible using the Apple II+ and the KB6000. B-scans, which give an ultrasonic cross-sectional view of indications in the workpiece, previously required about ten minutes to half an hour to produce and were in black and white. Now B-scans with colour coded amplitude information can be produced in as little as ten seconds.

Ultrasonic Angle Beam Compensation Software

When B-scans are done with angle beam probes, the resulting image is skewed. A special graphics processing routine has been written to correct these images. The angle correction processing requires only seconds.

Bruce A Unit 1 - Ultrasonic Inspection of Pressure Tube L-08

During a routine inservice eddy current inspection of Bruce A Unit 1 pressure tubes, an anomaly was found in tube L-08. AECL-CRNL provided portable inchannel inspection equipment and personnel to perform an ultrasonic inspection. Research personnel assisted with the inspection and the interpretation of results. The anomaly was located approximately half way down the tube at the 2 o'clock orientation. It was an inside surface breaking defect approximately 15 mm long and less than 1 mm deep with some subsurface volume.

3.0 NDE TECHNIQUES R&D AND APPLICATIONS

3.1 Acoustic Emission

Pickering A Garter Spring Movement

The recent failure of a pressure tube has raised concern about the location of fuel channel garter spring spacers.

A tube vibration program at AECL Sheridan Park was instituted to determine if garter springs can and do move. It was noted that at a certain amplitude of vibration the springs started to chatter and chirp. Because of the audible acoustic activity, acoustic emission was considered to be a potential method of detecting garter spring movement and, with its source location capabilities, also a method of pinpointing the location of the springs.

Various AE systems in the possession of Research Division were used, first on the fuel channel in the Pump Test facility as a trial run, and then on a fuel channel at AECL. Detection of chirping garter springs and location of the springs met with limited success because of (i) the apparent lack of detectable impacting signals from the vibrating springs, (ii) the low

sensitivity of the AE systems and (iii) the available fuel channels at Pump Test and Sheridan Park aren't truly representative of a Pickering fuel channel. Future work will consist of making a mock calandria tube for the bare pressure tube in Pump Test, inserting the springs and somehow vibrating the channel. Enhancement of system capabilities are also planned by using updated amplification instrumentation, interfaced to the laboratorie's 12 channel computerized AE system.

AE Studies on the High Pressure System

A pressure vessel, onto which coupons can be attached and then fatigue cracked for acoustic emission crack monitoring, has not been operational for most of the year because of problems with the pump set. Specifically, the rubber bladders that act as a barrier between hydraulic oil and water have developed holes resulting in contamination of the hydraulic oil. The three bladders have been tested for leaks and the faulty one replaced. Once the system is operational again, acoustic emission studies on crack propagation, analysis and characterization will resume.

Pickering A Manway Hinge Removal Program

Hinges, that enable covers on manway entrances to swing out of the way when required, are deteriorating under the influence of flow of the primary coolant. These manways are located on the hemispherical head on the bottom of the system generators. Over the years some hinges have broken off and as a result a hinge removal program has been instituted. Since not all the hinges in every boiler of a particular unit at Bruce and Pickering can be removed in one shutdown period, an on-line monitoring program to determine worst case situations for priority removal was considered. A trial run monitor of Boiler 5 in unit 3 at Pickering was decided on.

Two AE sensors were mounted on the boiler, one on the inlet manway cover, the other on the hemihead material one meter away from the first one. The dual sensor installation permits source location of the impacting manway hinge.

The monitor was to commence on unit startup with subsequent checks at monthly intervals. The first data recording session was delayed approximately 7 months because of the acute manpower shortage created by the shutdown of Units 1 and 2 in the wake of the pressure tube burst. At this time, the monitor indicated events were occurring at sensor A on the manway cover, whereas sensor B seemed to be inactive. Because of sensor B's inactivity, the source location technique was inoperable.

Monitoring of the hinge using sensor A will continue with the use of a digital oscilloscope which can record long and short duration sweeps. The long sweep will record a number of events and the short sweep will focus on individual bursts. Changes in number of events and characteristics of individual burst will chart the deterioration of the hinge.

TWE - Hydraulic Cylinder From a Manlift Device

A hydraulic cylinder failed explosively along a resistance welded seam weld down the length of its body causing serious injury to the operator of the manlift device. Four similar cylinders were ultrasonically inspected and the one with the most defects was selected to undergo a burst test at the TWE workshop. This cylinder was monitored with acoustic emission (AE) right up to failure. Two sensors were mounted on the cylinder one at each end providing the capability of source locating the events. The imminent failure of the cylinder was also clearly indicated by the fast rising slope of accumulated counts versus load curve. The cylinder eventually failed at the circular weld at the pivoting end. A report was issued which also recommended that acoustic emission be considered as a means of testing the structural integrity of suspect cylinders.

BHWP - Acoustic Emission of an Absorber Tower

An absorber tower at BHWP due to retire from service because of blistering in the top portion of the tower, was scheduled for burst testing to failure. NDE requested the opportunity to monitor the absorber tower with their twelve channel computerized acoustic emission system. The tower ultimately was not taken to failure but stressed to a level where significant yielding occurred. Twelve sensors were used to source locate the events as the vessel was hydrostatically loaded to 4.3 MPa.

The acoustic emission sources could not be correlated to the blistering in the tower. Rather the sources were located in the area of gross yielding and flaking scale. The structural integrity of the vessel remained intact.

Bruce A Pressure Tube Leak Detection

The pressure tube leak search at Bruce GSA Unit 2 in late 1982 required 10 or more full face reactor scans before leaks in channels A14 and J11 were positively identified. The numerous scans resulted in a larger leak rate at which point the rms value of the leak source increased above the background noise level. A program was started at Research to try and identify very low level leak rates by trying to characterize and separate leak noise from background noise.

The first step in the program was to simulate a leak from a pressure tube. Several attempts using an aluminum pressure vessel into which was drilled a small hole and tapered screw to close it off failed to produce an adequate leak signal. Pipe threaded plugs with a longitudinal slot cut across the threads also failed to produce a characteristic signal. The final solution was a vessel constructed from a section of pressure tube material into which was drilled a small hole and a Morse taper pin lowered into the hole by a fine threaded screw. The vessel could be pressurized to 10.3 MPa.

In progress now is the fabrication of a pressure vessel consisting of a proper endfitting and a short pressure tube stub rolled into the endfitting. This vessel can be heated and pressurized to duplicate the operating conditions of a Pickering and Bruce fuel channel. The Morse taper technique will be used to produce a controllable leak source. Data will be collected and analyzed with a sophisticated digitizer.

3.2 Ultrasonic Testing

Pickering A - Inspection of Notches in Zr II Test Tubes

A hydrided Zr II notched pressure tube was inspected ultrasonically after cyclic testing till leakage occurred. Normal and shear-wave C-scans, shear-wave B-scans, axial and circumferential amplitude traces and pitch-catch were used. Three of the four notches on endfitting F had grown to near through-wall or failure, though it was not possible to determine which of the three notches had leaked. In endfitting E, none of the four notches had grown substantially radially, but did appear to have propagated inboard a small amount. A second tube has been inspected.

Pickering A - B-Scan of Boiler Manway

A B-scan imaging system was developed for inspecting boiler manways from the inside of the manway. The system consisted of an Apple II plus computer, Krautkramer KB6000 flaw detector, driver, scanning apparatus and immersion probes. A mock-up of the manway with side-drilled holes was manufactured, and inspected both manually and with the B-scan. The B-scan approach showed substantially improved imaging over the manual inspection. Boiler 11 in Pickering Unit 2 was also inspected using the B-scan. Most of the reflectors appeared small, though sizing was difficult due to defocussing of the ultrasound beam. None of the reflectors appeared to have grown. The main problems experienced were reproducibly normalizing the probe, carrying the heavy equipment up the boiler, and defocussing of the ultrasound beam.

Pickering A - Mechanical Ultrasonic Scanner for Manway Inspection

A request was received from Central Nuclear Services to investigate the possibility of developing a mechanical ultrasonic scanner for manway ultrasonic inspection at Pickering NGSA. The compound contour of the steam generator head around the manway causes major difficulty in the ultrasonic inspection and in the design of such a mechanical scanner. A prototype mechanical scanner has been quickly build and used for such a manway ultrasonic inspection in mid 1983. Some minor problems reported will be modified so that a satisfactory scanner can be developed for any conventional manway inspection. The scanner promises to enable the operators to obtain a good transducer position repeatability. Manipulative motion control of the probe holder in the current design has been employed. More sophisticated control could be considered at a later date it if is found necessary or economically justifiable.

BHWP - Inspection of E3 Hot Tower

Due to erosion/corrosion on the inside surface of E3 third stage hot tower, the NDE unit was requested to perform ultrasonic mapping of two selected areas. Initially distance colour coded C-scans were performed, and subsequently normal beam B-scans. The towers were operating at about 110°C, and water was used as the couplant. The results agreed well with the BHWP D-meter inspections.

Inspection of Autoclaves

A number of stainless steel autoclaves containing various welds were carefully pre-service inspected using immersion ultrasonics, and the results stored on diskette. The autoclaves will be operated in a corrosion loop for about a year, where there is a possibility of some corrosion/cracking occurring. After this period, the autoclaves will be reinspected using the same equipment to determine how reproducible these inspections were and also whether any changes had occurred.

Lakeview TGS - Tandem Probe Inspection of Economizer Inlet Header

A tandem probe ultrasonic inspection system was developed to detect and size thermal fatigue cracks in economizer inlet headers using a mock-up with notches and a cracked section of a used Lakeview header. Notches and cracks were reliably detected, but oversized by about 10 mm, most likely due to beam spread. Signal amplitudes varied by several decibels, apparently due to surface roughness. Signals were fairly constant over an arc of $\pm 1^\circ$ around the mid-plane between the header outlet holes. An in-service inspection system was described.

TWE - Hydraulic Cylinders for Manlift Devices

Following the sudden failure of a cylinder in service along the ER seam weld, four other cylinders were provided for ultrasonic inspection. 100% volumetric inspection was performed, using a computer-controlled immersion scan oriented for axial-radial defects. One of the four cylinders showed particularly large indications, and was selected for subsequent burst testing.

Remote Inspection of Used Fuel Containers

Eight marginal titanium diffusion bonds were ultrasonically inspected using previously developed techniques. A new, very highly focussed immersion probe showed improved performance over more conventional probes.

A series of thick titanium, Inconel and copper welds were being prepared for ultrasonic examination to determine the degree of weld anisotropy.

CEA - EMATS

A Canadian Electrical Association contract on developing an EMAT device (ElectroMagnetic Acoustic Transducer) to measure the wall thickness of thermal plant boiler tubes at UKAEA, Hrawell, is being monitored. The prototype EMAT device appears to work fairly well, even on heavily scaled tubing. A final industrial prototype will be developed for trials on an Ontario Hydro boiler in the spring of 1984, using a portable box and microprocessor-controlled signal processing.

3.3 Eddy Current Testing

Quantization of Errors in Eddy Current Measurements

A proposal has been written for CNS describing a work program to evaluate the magnitude and sources of errors in the current procedures for the eddy current inspection of Inconel steam generator tubing. The results of this program would allow one to put realistic error bounds on the depth measurements of defects similar to those used to calibrate the system. It would also indicate areas for possible improvement of equipment or techniques.

Douglas Point NGS Fuel Channel Inspection

During the routine shutdown of Douglas Point NGS, an eddy current inspection of reactor fuel channels K9, K20, L11 and N15 was requested by Douglas Point. CNS supplied a normal 3 mm pancake probe and Research supplied a new developed differential pancake probe. Both probes were used in the inspection. No defect indications were observed in any of the fuel channels inspected.

Eddy Current Measurement of Pressure Tube Crevice Corrosion

Early work with very small (1 mm diameter) pancake type coils for profiling wide shallow surface defects in pressure tubes such as crevice corrosion was promising. However, the depth resolution of such probes was very limited. A number of new probe designs including absolute and differential tangential coils with and without ferrite focussing were developed and tested. The response of all probes was affected by the defect volume. However, with the focussed probes, an estimate of defect width could be estimated allowing the depth to be approximately deduced for defects up to .8 mm deep. Work has commenced on probe designs capable of providing better results to deeper defects.

3.4 Miscellaneous

CTS - Cost-Benefit Analysis on Thermal Plant Turbine Bolting

A Monte Carlo analysis of thermal plant turbine bolting was performed on a modelled unit, comparing three different approaches - current practice, regenerative reheat-treatments and nondestructive evaluation. Various scenarios were considered, and sudden forced outages were shown to be the dominant factor, if they occurred. For the most likely scenario, estimated benefits for all thermal units lay between ~\$1.4 m and \$3.5 m, but the accuracy of the results is severely limited by the inadequacy of the data available.

Inspection and Consultations in Support of Research Division

Many inspections or consultations in inspection methods have been performed for other groups within Research Division. These have included Metallurgical Services (defect location in failure analysis subjects such as steam generator tubes). Metallurgy (testing of tubesheet overlay specimens), Mechanical Testing (valve position monitoring with ultrasonics and ultrasonic detection of water level in a reservoir), Pump Test Facility (advice on inspection of welds in PHT piping), Electrical Research (location of crack in 50 mm diameter pipe) and Geotechnical Research (crack detection in granite boreholes and casting of rubber seals in boreholes for pressure testing).

Pickering NGSA - Miscellaneous CCTV Inspections

Assistance was provided to Pickering Operations and CNS on a number of occasions by performing CCTV inspections in difficult locations. Of particular interest were the inspections of the ruptured pressure tube in Unit 2 and subsequent video inspection of the bellows and calandria tube. Inspections of feeder pipes to look for possible contacts were also performed.

4.0 GAUGING TECHNIQUES AND INSTRUMENTATION

Pickering NGSA - Endshield Absolute Separation Measurement Device

At Central Nuclear Services' request, a linear distance measurement device has been devised for checking the endshield absolute separation at Pickering NGSA. A special manipulative tool equipped with a Lovar tape was fabricated and tentatively tested in a mock-up channel in the Research laboratory. The Lovar tape has been calibrated and certified; and it has a very low thermal expansion coefficient. The tape is designed to be pushed through any inspected channel by several push rods, which are handled by operators. It is anticipated that the device will be tested in the station mock-up channel before commissioning so that a detailed operating procedure can be set.

Pickering A - Manual Feeder Clearance Tools

Two manually operated tools, identical to those devised for measuring the spacings between feeder pipes at Pickering NGS B and Bruce NGS, have been manufactured and successfully used in Pickering NGSA.

Pickering A - Laser Device for Pressure Tube (P/T) and Calandria Tube (C/T) Sag Measurement

At Central Nuclear Services' request, a set of laser devices for measuring the amount of sag in a pressure tube and a calandria tube has been devised for Pickering A. The device, employing the Bruce A laser sag measurement method, consists of a 3 mw He-Ne laser fixture, four endfitting mounting caps and two slope measurement devices. Two of these endcaps are devised for P/T sag measurement whereas the other two caps are made for C/T application. All caps contain glass plates on which mylar gratitudes are attached. A side mirror (20 cm x 40 cm) is also required to allow the operator to look down the channel to observe the reflection without entering the (gamma) radiation beam from the channel. The slope measurement devices are used to detect the endfitting tilt. These devices have been satisfactorily tested in the station mock-up channel.

Bruce B - Scanning Tool for Elongation Measurement (STEM)

Four online scanning tools and the control console, for measuring the relative distance between the end of each endfitting and the scan plane of the fuelling machine, have been manufactured for Bruce B, units 5 and 6. These devices are identical to, and perform the same function as, the Bruce A STEM devices. Two of these four STEM devices have been mounted on the fuelling machine carriage in unit 6. Preliminary testing has been successfully carried out. A preservice baseline measurement will be performed before criticality. Another two STEM measuring heads will be supplied to Unit 5 at Bruce B in mid 1984. These devices can be operated during reactor shutdown or during operation. The STEM operations require no man rem expenditure.

Douglas Point NGS - Direct Measurement Tools for Theodolite
Measurement of Fuel Channel Elongation

A remeasurement of fuel channel elongation on the Douglas Point reactor was carried out by AECL personnel during 1983. The theodolite method, developed by Research Division, was used. Two new direct measurement tools were manufactured and calibrated by Research Division for these measurements.

Pickering NGSA - Feeder Pipe Oxide Sampling Device

A method to remove an oxide sample from a feeder pipe during a fuel channel replacement was evaluated. The concept consisted of a rotating lap or brush, flexible drive shafting, centering discs, electric drill and vacuum collecting system. Tests indicated that the base oxide was extremely hard and tenacious so that uneven removal quickly led to contamination of the oxide with parent material. The concept was abandoned.

III - 1984 WORK PROGRAM OUTLINE

1.0 FRACTURE MECHANICS RESEARCH

Post Yield Fracture Mechanics

A joint project with Design and Development, Mechanical Design Dept., will be conducted to investigate the utility of the tearing instability analysis of PHT piping defects. Existing technology will be implemented and applied to a Darlington piping configuration to provide a realistic basis for assessing the technique.

Computational Fracture Mechanics

The analysis of three dimensional cracks is presently a hopelessly costly and time consuming process. Although preferable, it is virtually impossible to perform such analysis for ASME Sect XI evaluations. A weight function technique will be further extended by assembling the "pieces" developed in 1983. This will entail the preparation and documentation of a number of computer programs, and verification of the technique by applying it to a series of test cases.

Critical Crack Length of Pressure Tubes

It is anticipated that further compact tension specimens of Zircaloy-2 and Zr-Nb with radial and/or mixed hydrides will be supplied by the Nuclear Metallurgy Unit for testing in order to determine the fracture toughness and hence critical crack length of pressure tubes.

Double Torsion Tests Using Pressure Tube Segments

Double torsion tests using curved segments of pressure tube material with different hydride morphologies will be carried out to study statistical variations in fracture toughness along the axial length of tubes and away from rolled joints. Crack arrest fracture toughness may also be studied using longer specimens.

Delayed Hydride Cracking Tests Using Pressure Tube Material

There is a need to study stage II/III of delayed hydride cracking for pressure tube material with radial and mixed hydride morphologies. Such hydride cracking tests will be performed using curved double torsion specimens under incremental loading after an initial thermal cycle.

Fracture of Zr-Nb Pressure Tube Material With Blisters

The Fracture Mechanics and Nuclear Metallurgy Unit will collaborate on a program to study the fracture characteristics of small specimens and pressure tubes of Zr-Nb with blisters. The growth of linear arrays of blisters of various sizes and spacings in material with different hydrogen concentrations will be studied.

Elastic-Plastic Fracture Mechanics Analyses of Pressure Tubes Containing Blisters

Elastic-plastic fracture mechanics analyses of Zr-Nb pressure tubes due to the volume expansion of blisters will be performed as a part of a task for determining the time between PT/CT contact and fast fracture. The first part of the project will be stress analyses of Zr-Nb pressure tubes considering various blister sizes and blister spacings. The second part of the project will be the calculation of crack driving forces at crack tips associated with blisters. Various combinations of blister sizes and crack lengths will be considered.

Elastic-Plastic Fracture Mechanics Methods

Efforts will continue to keep abreast with rapid developments in EPFM methods such as EPRI engineering approach and CEBG R-6 approach. Emphasis will be on applying EPFM methods to the integrity assessment of plant components.

Mixed Mode Fatigue Studies

In real structures, cracks are often situated at an angle to the applied loads or are subjected to combined loads, resulting in mixed mode fracture conditions. Therefore, there is a need to develop some basic understanding of engineering fracture problems of a practical nature. Fatigue crack growth tests for part through cracked specimens will be performed under combined loadings of tension and bending. Fatigue crack growth tests on specimens with angle cracks will also be performed under tension loadings.

Dynamic Fracture Mechanics Methods

Analytical methods will be investigated with a view to identifying the parameters which can influence the driving force of a running crack. A finite element method for dynamic fracture analysis will be developed. This work is also directed at identifying the conditions for crack arrest.

Fatigue and Fracture Toughness Properties of A516 Gr 70 Welds

Fracture toughness tests on A516 Gr 70 pressure vessel steel will continue to assess the integrity of the heat affected zone (HAZ) after a non-PWH weld repair. Charpy sized three-point-bend specimens will be used in these tests. Fatigue crack growth tests will also be performed on both HAZ and base plate specimens.

2.0 NONDESTRUCTIVE INSPECTION RESEARCH AND DEVELOPMENT

CIGAR

CIGAR will be completed in 1984. The main activity remaining is the completion of software for entering various styles of reactor channels and the scan and data collection software for some inspection systems. Replacement drive rods and inspection heads are expected in early February. Completion of software and testing should be complete by mid year. An on reactor trial, preferably on a clean reactor, should be possible before year end.

CIGAR-ette

The CIGAR-ette system currently being used for inspection of pressure tubes in Pickering Units 1 and 2 utilizes the CIGAR inspection head and inspection systems developed by Research Division. Assistance will be provided to assure the smooth operation of the system, to assist with data interpretation and to develop changes, or new systems as required.

Remote Inspection of Used Fuel Containers

Ultrasonic examination of the mild steel, stainless steel, titanium grades 2 and 12, Inconel 625, Hastelloy C-276 and deoxidized copper will be performed by a Waterloo co-op student. A re-inspection of the prototype thin-walled titanium used fuel container will be performed, if required. If time permits, the PUMA robot plus waterjet will be used to inspect titanium diffusion bonds to illustrate the in-service feasibility of this approach.

Development of Automated and Robotic Inspection Systems

Consolidation and documentation of Apple programs written for automated scanning for ultrasonic testing will be carried out. The capabilities will be expanded to include collection of many B-scans and software creation of C-scans. Other computer systems are being considered to enhance the speed and capabilities of the system.

Further developments of the 2nd scanning tank will take place. It will be used for parametric studies of flaw detection on PHT system weld geometries.

Robotic Scanning System

A new set of development goals will be established. This will include the adaptation of the PUMA 560 robot to remote inspection capability in field applications.

Acoustic Emission (AE)

Lakeview TGS - a system will be developed for online monitoring of cracking in Economizer Inlet headers.

Research - development work on online integrity monitoring of pressure vessels and piping will continue using the recently commissioned Research Pressure Vessel Test facility.

CNS - development work on detection of small pressure tube leaks will proceed with full scale mock-up tests.

CNS - development work for nonintrusive detection of garter spring location will be pursued.

Pickering A - B-Scan of Manways

If CNS are interested, an improved B-scan inspection system could be developed based on either immersion or contact ultrasonics, using a special purpose flaw detector with focussed probes or synthetic aperture focussing.

BHWP - Development of Portable Inspection System

Following the successful inspection of E3 third stage hot tower the NDE unit was asked to develop a fully portable inspection system capable of profiling erosion/corrosion areas.

Ultrasonic Testing

Lakeview TGS - further development and application of the tandem method of sizing crack depths in Economizer Headers will take place.

Nanticoke - Turbine rotor blades. A method of detecting small cracks in the turbine blade fir tree will be investigated.

Pickering NGS - Pressure Tube Flaw Detection - work will be performed to provide better definition of system calibration and sensitivity checking. The use of line focussed transducers for pressure tube inspection will be explored and comparisons between the CIGAR and CRNL inspections will be made.

Pickering - Pressure Tube-Calandria Tube Gap - the method of accurately measuring PT/CT gap ultrasonically with a flooded annulus will be documented.

Research - crack tip diffraction methods for crack depth measurement will be investigated possibly using the robot for controlled scanning.

Research - an ultrasonic inspection system operating up to 100 MHz, consisting of 400 MHz digital oscilloscope, 100 MHz pulser-receiver and various probes will be used to inspect pressure tubes to attempt to measure hydride platelet concentration.

Eddy Current - (EC)

CNS - pressure tube crevice corrosion and deep defects - New coils will be developed to provide improved resolution for full pad crevice depth measurement and depth estimates of deep defects.

CNS - Steam Generator Tubes - a parametric study to determine the influence of various factors on the errors in sizing various defects in steam generator tubes using EC will be undertaken.

CNS - Pressure Tube-Calandria Tube Gap Measurement - further work to improve the accuracy of PT-CT gap measurement will be undertaken.

Research - Pulsed Eddy Currents - further work is planned for developing this technique. Preliminary work shows it has promise for application to many complex problems such as flaw identification in tubing at baffle and support plates, pilger noise, etc.

Research - Modelling of EC Applications - methods of mathematically modelling the interaction of the field generated by various EC coils and workpieces with various flaws will be investigated.

Gauging Techniques and Instrumentation

Bruce B - Scanning Tool for Elongation Measurement (STEM) - four measuring mechanisms will be manufactured and debugged for Bruce B Unit 7 and 8.

Pickering A - Mark II Spotface Measurement Tools - three sets of the spotface tools will be designed and developed. This work includes development of a new set of digital dial gauges.

Bruce NGS - Manual Gauges for Feeder Pipe - Grayloc Clearance Measurements - a measuring device will be developed to measure the gaps between feeder pipes and yokes.

IV - SUMMARY

Ideally, a research unit such as the Nondestructive and Fracture Evaluation Section should be involved in a spectrum of projects ranging from the long term to the immediate. There is no definable transition between long term, medium term and short term but rather, as time passes the long term projects become medium term and the medium term come to fruition as the newly developed technology is transferred to those responsible for operations. This is a dynamic process in that, not only is there movement from long to short term, but projects are added and dropped at all levels of involvement. This process is essential because short term needs can only be met when the underlying knowledge acquired through forward looking research is in place to enable such endeavours to occur. For example, Pickering NGS Units 1 and 2 inspections using the CIGAR-ette devices were very quickly underway with considerable success but only because we had previously developed the knowledge of what was needed for such an inspection. This included approximately 2 years prior research into radiation resistant ultrasonic transducers. 1983 was characterized as a year of addressing the short term needs of the Corporation and it is anticipated that this will continue through 1984. There is considerable concern that the Section does not have the resources to tackle these short term demands, let alone put into place a work program with a sensible balance between forward looking research and short term work involving technology transfer to operating groups.

Following completion of rolled joint inspections in Bruce NGS, Unit 2 early in the year, much of the effort of the NDE Unit was directed towards CIGAR. The CIGAR system was delivered uncompleted to Research Division in August and since that time many of the inspection systems have been completed and integrated into the system as a whole. A number of "bugs" have been identified, some more major than others, but most are now in resolution. Late in the year, the NDE Unit became deeply involved in the fuel channel inspection requirements following the Pickering NGS Unit 2, channel G16 rupture. Concern quickly arose as to the location of garter springs in other channels and the Unit responded with the rapid development of an eddy current probe that would indicate their position. Shortly after this the decision was made to initiate large scale fuel channel inspection and the unit was called upon to help make this possible through provision of the inspection system known as CIGAR-ette. This system required cannibalization of the CIGAR system as use was made of the CIGAR inspection head, drive rods and instrumentation. Even when CIGAR-ette was in full use, development continued in the way of generating isometric displays of ultrasonic scans and the full support of the NDE unit was made available to support this effort.

The total effort in support of CIGAR-ette had adverse consequences on the work program of the NDE Unit in that CIGAR commissioning could not proceed due to use of essential components by CIGAR-ette and that other projects had to be delayed or dropped. However, progress was achieved in the area of inspection automation and data displays. This effort allowed us to assist BHWP in mapping areas of corrosion in one of the towers, and in mapping defects in a Pickering NGS steam generator manway.

Resources limited the amount of effort in the area of acoustic emission technology but some progress was reported in a number of projects including pressure tube leak detection and pressure test monitoring.

A number of requests for assistance were received in terms of precise spatial measurement equipment. These included end-shield separation measurement, feeder clearance measurement and fuel channel elongation measurement. Also, personnel from the Unit performed pressure tube and calandria tube sag measurements using a laser device designed and fabricated within the Section.

In terms of the plant materials test program, major efforts were directed at pressure tube materials - Zircaloy and Zirconium-2.5% Niobium, although work is also reported in fracture toughness testing of A516 Gr 70 in support of temper bead weld repair and in determination of the low cycle fatigue properties of 18 Mn-4 Cr end ring material. Fracture toughness testing of Zircaloy-2 material using C-T specimens showed that crack growth was primarily dictated by the presence of radial hydrides at low and intermediate temperatures but above the transition temperature the flow properties of the matrix dominated. These laboratory tests on Zircaloy-2 were augmented with burst tests and leak-before-break tests performed at Orenda Ltd. In similar burst tests using Zr-2.5 Nb material it was demonstrated that either plastic collapse or fast fracture could occur, depending on a number of parameters, especially hydrogen content. The requirement of deriving material parameters from burst tests is rather limiting and significant effort has been expended to augment this information through laboratory tests using small specimens. Of note is participation in a "Round Robin" exercise where a double torsion configuration has been used successfully.

Significant advances have been noted in the fracture mechanics laboratory. Each servo-hydraulic load frame has been equipped with a desk top computer which is used for frame control, data acquisition and processing. There has been extensive use of these computers to conduct J-integral tests. Additionally, an array of special purpose grips, jigs and electronic instrumentation have been designed and fabricated to meet testing needs.

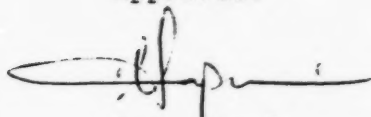
A number of structural integrity analyses were performed through the year. One of these involved a surface breaking defect discovered in the pressure tube of channel L08, Bruce NGS, Unit 1. The analysis clearly indicated the need for a workable pressure tube materials performance data base, which currently does not exist. Other aspects of computational fracture mechanics were also pursued, including continued development of elastic-plastic methods which was started in 1982. Although not yet used for a mandatory analysis of an in-plant component, both two and three dimensional analyses have successfully been used to model realistic components, including a pipe with a circumferential crack. Advances in terms of a desk top computer based ASME Section XI analysis capability are also reported.

The work program planned for 1984 does contain some scope for medium and perhaps long term projects but the main emphasis is on short term work related to the primary heat transport system of our reactors. It is hoped that some of the projects delayed by our direct involvement in the fuel channel problems at Pickering NGS may be restarted.

ACKNOWLEDGEMENT

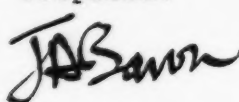
Both the accomplishments during 1983 and the written descriptions of them as they appear in this report are the work of all the Section staff. Their individual contributions to the overall work program for the Section and the contents of this report are most gratefully acknowledged.

Approved:



O.A. Kupcis
Manager
Metallurgical Research Dept

Prepared:



J.A. Baron
Supervising Engineer
Nondestructive and Fracture
Evaluation Section

/iz

NONDESTRUCTIVE AND FRACTURE EVALUATION SECTION
CONFERENCE PRESENTATIONS AND PUBLICATIONS
1983

1.0 CONFERENCE PRESENTATIONS

B. Mukherjee, A. Akthar*, R. Roberge** and M.D.C. Moles, "An Overview of Structural Integrity R&D in Canadian Electrical Utilities", Presented at the Thirteenth General Meeting of the International Electrical Research Exchange, October 1983, Arnhem, Netherlands by Dr. E.M. Ezer, Director of R&D, CEA.

B. Mukherjee and D.M. McCluskey, "Measurement of Fracture Toughness of Low-Pressure Turbine Discs From Charpy-Size Specimens", Paper #175, Canadian Institute of Mining and Metallurgy, 22nd Annual Conference of Metallurgists, Edmonton, August 21-24, 1983.

P.H. Davies and C.P. Stearns, "Axial Fracture Toughness of Zr-2.5% Nb Pressure Tube Material", Presented at the 16th National Symposium on Fracture Mechanics, August 1983, Columbus, Ohio.

Y.J. Kim, B. Mukherjee, D.W. Carpenter, "Effect of Hydrogen on Crack Initiation and Crack Growth in 18 Mn 4 Cr Steels", Presented at the 16th National Symposium on Fracture Mechanics, August 1983, Columbus, Ohio.

J.A. Baron, "Acoustic Emission Monitoring of Aerial Lift Devices", CEA Conference, Vancouver, March, 1983.

M.P. Dolbey and M.D.C. Moles, "Ultrasonic Assessment of the Quality of CANDU Reactor Fuel Channel Rolled Joints", ASNT Topical Seminar on Automated Nondestructive Testing, Idaho Falls, Idaho, June 28-30, 1983.

2.0 PAPERS PUBLISHED

M.D.C. Moles, "Tandem Probe Ultrasonic Measurement of Cracks in Economizer Inlet Header", Materials Evaluation, April 1984, Special Issue on Flaw Characterization.

J.A. Baron, A.G. Beattie, R.S. Algera and C.C. Feng, "Acoustic Emission Couplants II: Coupling Efficiencies of Assorted Materials", Journal of Acoustic Emission, Vol 2, No. 1.

J.A. Baron, "Status Report on Assuring the Structural Integrity of Aerial Personnel Devices", Canadian Electrical Association, Distribution Committee - SD-124.

* B.C. Hydro

** Quebec Hydro

2.0 PAPERS PUBLISHED (Cont'd)

M.L. Vanderglas, "Some Aspects of the Weight Function Method For the Calculation of Stress Intensity Factors", Proceedings of the 7th International Conference on Structural Mechanics in Reactor Technology, Paper #G/F 3/6.

M.H. El Haddad and B. Mukherjee, "Low Cycle Fatigue of a Pressure Vessel Steel of Elevated Temperature", Proceedings of the 7th International Conference on Structural Mechanics, Paper #L9/8.

M.H. El Haddad and B. Mukherjee, "Elastic Plastic Fracture Mechanics Analysis of Fatigue Crack Growth", Elastic Plastic Fracture: Second Symposium, Volume II - Fracture Resistance Curves and Engineering Application, ASTM STP 803, C.F. Shih and J.P. Gudas Eds, ASTM, 1983.

C.P. Stearns and B.M. Mukherjee, "A Personal Computer Approach to Automating Stress Corrosion Studies", Report of current research announcements, International J. of Fracture, Vol 22, #2, June 1983, pp R35-R38.

P.H. Davies, "An Elastic Plastic Fracture Mechanics Study of Crack Initiation in 316 Stainless Steel". Elastic Plastic Fracture: Second Symposium, Vol II - Fracture Resistance Curves and Engineering Application, ASTM STP 803, C.F. Shih and J.P. Gudas, Eds., ASTM, 1983.

3.0 PAPERS SUBMITTED FOR PUBLICATION

P.H. Davies and C.P. Stearns, "Axial Fracture Toughness of Zr-2.5% Nb Pressure Tube Material", submitted to ASTM after pres at 16th Nat. Symp. on Fracture Mechanics, August 1983, Columbus, Ohio.

Y.J. Kim and D.W. Carpenter, "Effect of Hydrogen on Crack Initiation and Crack Growth in 18 Mn 4 Cr Steel", submitted to ASTM after pres. at 16th Nat. Symp on Fracture Mechanics, Aug 1983, Columbus, Ohio.

4.0 ABSTRACTS SUBMITTED FOR CONFERENCE PRESENTATION

B. Mukherjee, M.L. Vanderglas and D.M. McCluskey, "Toughness Measurement and Structural Integrity Consideration of a Pressure Vessel", 5th International Conference on Pressure Vessel Technology, San Francisco, California, Sept 9-14, 1984.

Y.J. Kim and J.W. Prince, "Integrity Evaluation of Temper-Bead Weld Repairs in Pressure Vessels", 1984 Pressure Vessel and Piping Conference, San Antonio, Texas, June 1984.

P.H. Davies, M.Leger, G.K. Shek and C.P. Stearns, "Fracture Toughness Testing of Zircaloy-2 Pressure Tube Material with Radial Hydrides using DC Potential Drop", 17th Nat. Symp on Fracture Mechanics, ASTM, Albany, NY, Aug 7-9, 1984.